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JET SHAPES IN HADRON AND ELECTRON COLLIDERS

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Abstract

High energy jets are observed both in hadronic machines like the Tevatron and electron machines like LEP. These jets have an extended structure in phase space which can be measured. This distribution is usually called the jet shape. There is an intrinsic relation between jet variables, like energy and direction, the jet algorithm used, and the jet shape. Jet shape differences can be used to separate quark and gluon jets.

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1 Introduction

QCD calculations have evolved dramatically since the early days of tree level calculations for the basic hard processes, both in e^+e^- and $p\bar{p}$ processes. Next to Leading Order calculations (NLO) exist for inclusive jet cross-sections [1] and other hard QCD phenomena.

Major advances have also occurred in understanding the soft part of QCD. Parton-Hadron duality [2] and Leading Log Approximation [3] eventually led to understanding jet fragmentation down to a scale of the proton mass.

In spite of all this advances, confinement is still poorly understood. It is important to measure and understand the inner structure of particle jets, in hope that it will give us helpful clues to solve this problem, in conjunction with the study of hadron spectroscopy.

A measurement of jet shapes is very interesting mainly because in a single measurement, both the hard and the soft part of QCD are probed. Near the jet axis, the shape is dominated by collinear soft gluon emission. At large angles (i.e at the edge of the cone), the shape reflects large angle gluon emission, which can be calculated perturbatively.

In this paper we present what has been learned about jet shapes, mainly in $p\bar{p}$ collisions, as measured by CDF [4]. The main source of data on jet shapes from e^+e^- collisions is an analysis by the OPAL collaboration from LEP [5], where differences in the shape of quark and gluon jets are demonstrated. More on this analysis can be found in the contribution by M. Thomson to this conference.

2 What is a Jet?

One of the hardest questions in jet physics is “what is a jet?”. As a jet is a distribution of energy and particles associated with a hard QCD process, the precise definition of a jet depends on how one ‘truncates’ this distribution. The ‘truncation’ is performed by a jet finding algorithm.

There are mainly two types of jet definitions. One is the Sterman-Weinberg [6]

which defines the jet in terms of an energy flow in a cone. The jet is required to have energy above a value inside the cone. Jets are separated by their angular distance. This type of jet definition are used extensively in hadronic colliders [7]. In this case the cone is drawn in coordinates which are invariant w.r.t. boosts along the beam axis. The coordinates then are the pseudorapidity $\eta = -\log \tan(\theta/2)$, the azimuthal angle ϕ and the transverse energy E_t . θ is the polar angle.

The other is basically the so called JADE algorithm, where jets are defined by their invariant mass [8]. Jets are separated if their invariant mass is greater than a predefined value. Several variations exist when this definition is turned into a jet algorithm. They differ by how they combine particles into jets and also there are several ways in which the mass is weighted by the momentum of the particles or modified to reflect the momentum w.r.t the jet axis. Although this methods are supposedly invariant under boosts, in practice this class of jet algorithms is mainly used in e^+e^- colliders, where the lab frame is also the center of mass frame.

Particle association with jets will differ for different jet algorithms. For example, in the JADE algorithm soft particles could be associated with a jet, even if they are distant in angle space from the jet core. In cone algorithms this is impossible. On the other hand a particle which was associated initially with the jet may be lost if it falls outside of the cone. The overall effect is that jets found by the different algorithms have slightly different jet shapes.

The different way in which jet cores are defined in the various algorithms also affects the measurement of the jet shape.

3 Jet Shapes in $p\bar{p}$ collisions

Following the CDF collaboration [4], the jet shape is defined here as the normalized transverse momentum flow of charged tracks inside a jet of cone R where $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, η is pseudorapidity and ϕ is the azimuthal angle. Jets have transverse energy E_t . Transverse is calculated w.r.t. the beam axis.

Within the framework of NLO QCD calculations it is possible to obtain more than one parton inside the cone. The jet energy is shared between these two partons. This effect produces an energy distribution inside the jet cone. At high enough energies,

where fragmentation effects become negligible, this distribution should be measurable.

The CDF's jet shape analysis was done using only jet triggers data which required a calorimeter cluster with at least a predefined value of transverse energy. The jets were required to be reconstructed in the CDF central calorimeter.

Tracks were used to study the jet shapes because of their better spatial and momentum resolution for single particles. The shape distribution is obtained by histogramming for each track in a jet its distance r ($= \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$), weighted by its transverse momentum (P_T), and divided by the total transverse momentum carried by tracks in the jet (\mathcal{P}_T^{jet}). This distribution is then normalized by dividing it by the total number of jets in the sample \mathcal{N}_{jet} . Note that only tracks with momentum above the minimum momentum measured by the CDF central tracking chamber P_T^{min} ($=0.4$ GeV) and within distance $r < R_0$ ($=1.0$) of the jet axis contribute to the distribution. N is the number of these tracks. Mathematically, The shape is defined by the normalized average transverse momentum (P_T) density $\rho(r)$:

$$\rho(r) = \frac{\xi(r)}{\int_0^{R_0} \xi(r') dr'} \quad \text{with} \quad \xi(r) \equiv \frac{1}{\mathcal{N}_{jet}} \sum_{jets} \int_{P_T > P_T^{min}} \frac{P_T}{\mathcal{P}_T^{jet}} \frac{d^2 N}{dr dP_T} dP_T \quad (1)$$

The integral shape variable $\Psi(r) = \int_0^r \rho(r') dr'$ was used to compare data with theory.

The theoretical predictions for the integral jet shape are obtained by calculating the phase space for two partons, weighted by their E_T and the appropriate matrix element squared, between the inner cone r and the jet cone R_0 [9]. The result is normalized by the total Born cross section. Assuming that non-perturbative effects do not change the jet shape substantially, this quantity is $1 - \Psi(r)$, from which the theoretical $\Psi(r)$ is extracted. This procedure is used in order to avoid collinear singularities at $r = 0$.

Before theory and experiment can be compared, one ambiguity has to be resolved: The problem of jet separation. In theory, two partons are separated if they are more distant than $2R$. Experimentally, there are cases where the tails of the jets overlap and the separation between the jet cores is less than $2R$. For the jet algorithm used in CDF [4] the minimum separation is typically $1.3R$ — $1.4R$. Thus, a new parameter was inserted in the theoretical calculation [9]: R_{sep} , which is the minimum separation between two jets.

In Fig. 1 we show both the definition of the variables and the comparison between CDF data and theory. The theory points were calculated for 100 GeV E_t jets. The

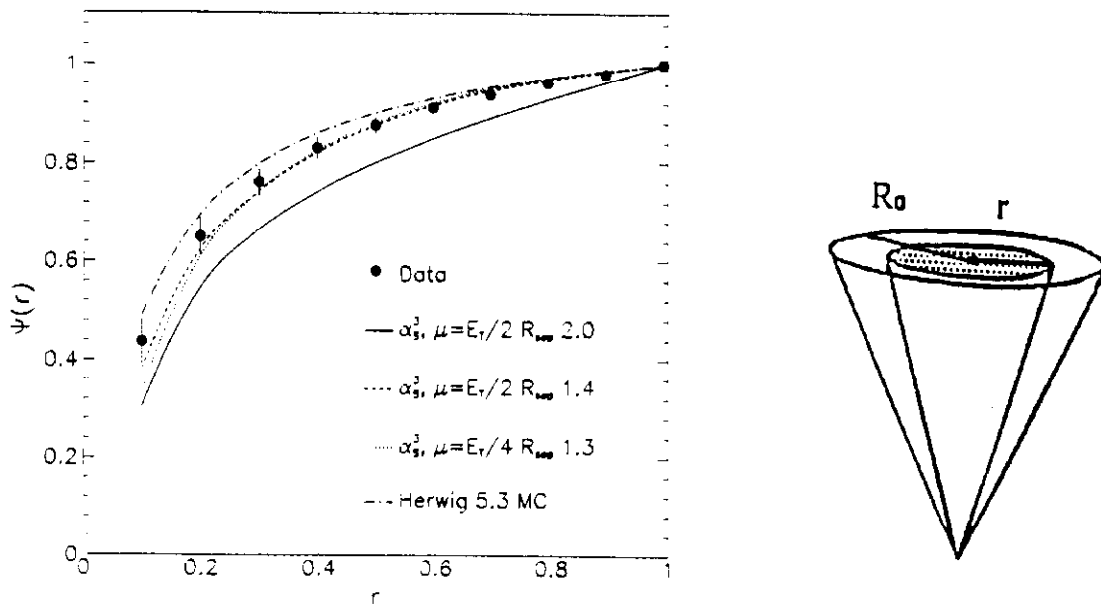


Figure 1: Variables and the integral shape of 100 GeV jets.

jets in the data were required to be central, namely $|\eta| \leq 0.7$, and to pass the cut $95 < E_t < 120$ GeV, when the jet E_t was corrected for detector effects. The shape distribution was corrected for known detector effects.

The CDF data show good agreement with theory [9] for a cone $R = 1.0$. Two parameters affect the theory curve, R_{sep} and μ , the renormalization parameter. The result varies by less than 25% when these parameters are changed within reasonable limits.

In order to compare the CDF data to theory and to QCD Monte Carlos, the energy dependence of the shape is shown in Figure 2 by plotting the fractional P_T inside of a cone of $r=0.4$, for the three different energies. Also plotted are the predictions of the Herwig [10] and Pythia [11] Monte Carlos, with their respective default structure functions, DO [12] and EHLQ [13], and the predictions of the α_s^3 theory, using HMRSB [14]. The bands represent the uncertainty in the α_s^3 theory due to the renormalization scale.

The analysis was pursued farther by showing that all leading QCD Monte Carlos, Herwig [10], Pythia [11] and Isajet [15], predict quite accurately the jet shape (Fig. 3.a). Here the differential jet shape $\rho(r)$ of 100 GeV jets is plotted. One can attempt to

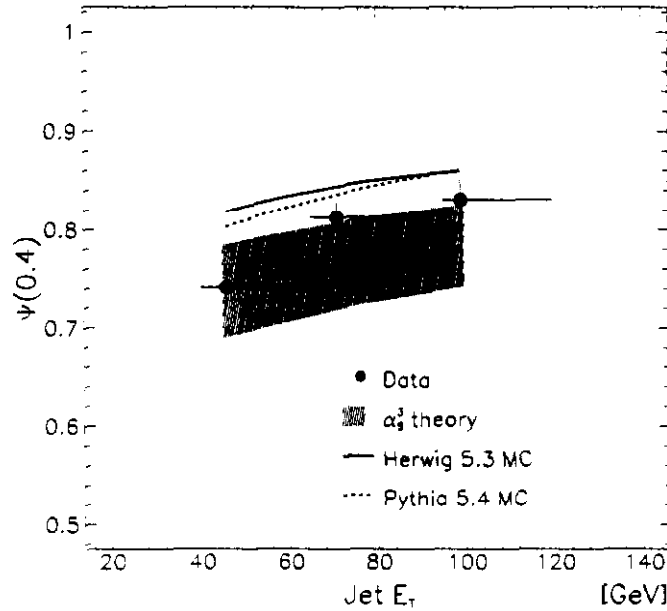


Figure 2: Variation of the jet shape with jet E_t .

separate the QCD shower contribution to the shape from the fragmentation contribution in the Monte Carlos. The shape obtained from showered partons in Herwig agrees with the jet shape formed by hadrons, while the shape obtained from Feynman-Field fragmentation without gluon radiation in Isajet diverges from the experimental data (Fig. 3b). Thus, we conclude that parton emission is the dominant process in forming the jet shape. One may try to use jet shape variables to classify quark and gluon jets, based on Monte Carlo predictions.

4 Jet Shape at LEP

Jet shape measurements at LEP were done in conjunction with a series of papers by OPAL on quark gluon separation[5]. The technique applied is simple, though powerful: In three-jet events, one selects events with topology of one hard jet and two softer jets. In the event plane the angular separation between the jets is 150° , 60° and again 150° . This topology ensures that the two softer jets have the same energy (~ 24 GeV). The hard jet is assumed to be a quark jet. One of the remaining soft jets is a gluon jet and

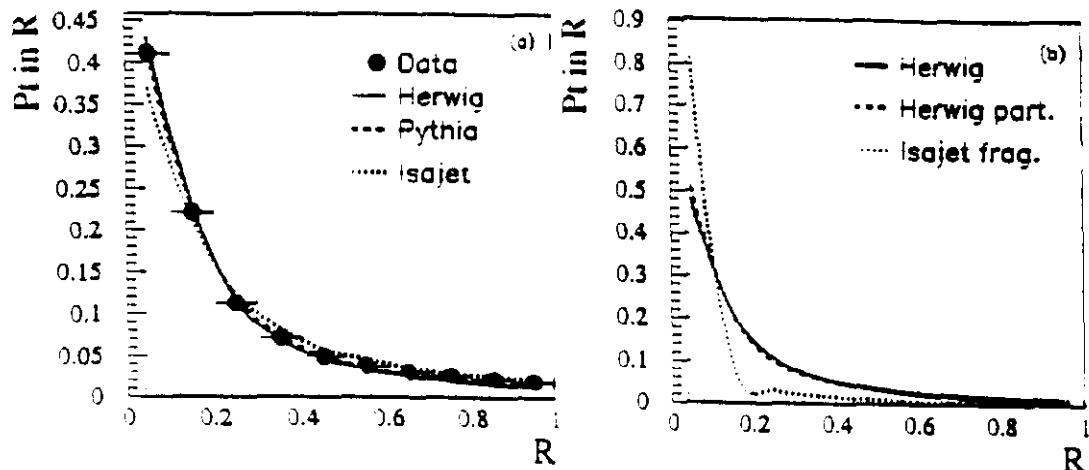


Figure 3: Differential Jet Shape for Data and QCD Monte Carlos.

the other is a quark jet.

To select the quark jet, b-tagging techniques were applied. Of the two different methods applied, b-tagging by vertex displacement and b-tagging by its semi-leptonic decay, the author prefers the vertex displacement method, because it does not require the presence of a lepton in the jet. The results quoted here, come from the vertex displacement method.

OPAL tagged 1175 b's in their selected sample. They obtained the gluon energy flow by looking at the untagged jet. In events where the a b quark cannot be found, one can still extract the jet shape for a mixture of 50% quark and 50% gluon jets ($\sim 20K$ -events). Differences in the jet shape of the mixed sample w.r.t. the jet shape of the quark tagged sample demonstrate that quark and gluon jets have indeed different jet shapes.

In Figure 4, we observe the shapes of quark and gluon jets in the three jet events in the event plane. Near the angle zero, the hard thin quark jet is seen, where the gluon and the mixed sample jet is seen at an angle of 150 degrees. The dots represent the pure gluon jet and the histogram line represents the mixed sample.

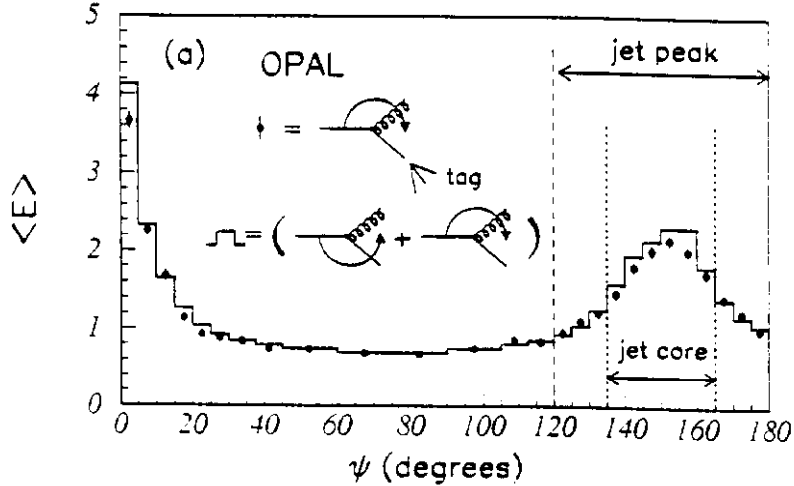


Figure 4: Energy flow in the event plane for gluon jets and for a mixed sample.

The gluon jets seem to be softer, i.e. the core is more depleted of energy than the mixed sample. More about this analysis can be found in the contribution by M. Thomson to these proceedings.

5 Jet Shapes and Quark Gluon Separation

OPAL has shown, as described in the previous section, that gluon jets have a broader shape than quark jets.

The CDF collaboration assumed that gluon jets have a broader shape, as predicted by QCD Monte Carlos, and used this information in an attempt to tag quark and gluon jets. Tagging quark jets is important in Top quark and other exotic particle searches.

A feed-forward Neural Network (NN) was used to discriminate between quark and gluon jets [16]. Of the 8 variables chosen, 3 sample the jet shape described above. The others are the charge multiplicity, the second moments of the η and ϕ distributions of the jet, and the P_t of the leading track and its distance r from the jet axis in η - ϕ space. The NN was trained on Pythia quark and gluon jets.

The NN outputs one variable, $qgval$, which is larger for quark jets than for gluon jets. In Fig. 5 we show the evolution of $\langle qgval \rangle$ with measured jet E_t . It is noticeable

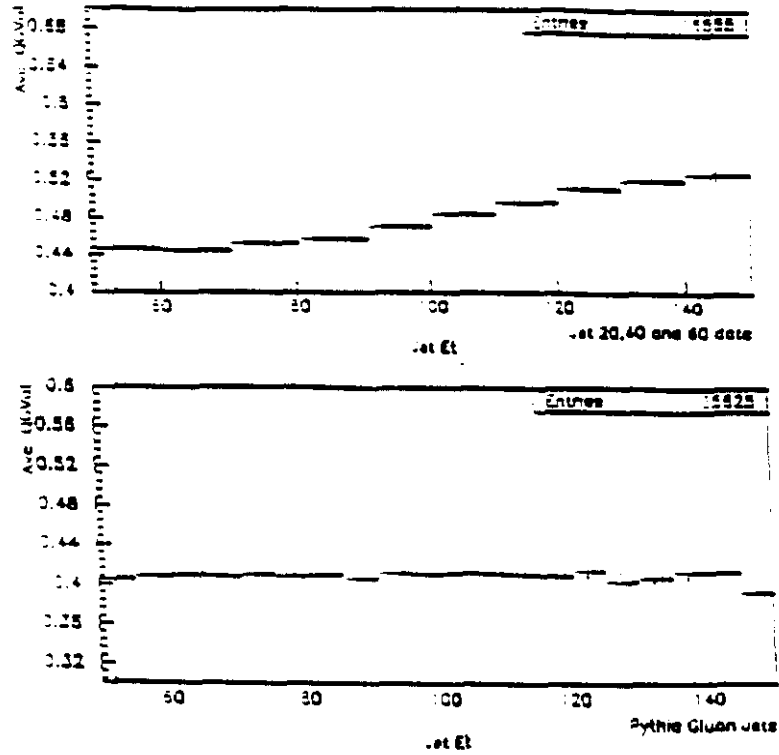


Figure 5: Dependence of the Neural Network Output with Jet E_t .

that $\langle qqval \rangle$ grows with jet E_t , while it is independent of jet E_t for a single species (quark or gluons).

This result can be interpreted as an increase in the fraction of quark jets in data at high energies, as expected from structure function behaviour.

Summary

Jet shapes are an almost ideal laboratory to test QCD. They probe the theory from different perspectives. It tests perturbative QCD as well as LLA parton showers. QCD Monte Carlos describe both e^+e^- and $p\bar{p}$ data quite well. The analysis of jet shapes in $p\bar{p}$ data lead to a better understanding on the importance of having identical jet algorithms applied in the experiments and in the theoretical predictions. Measured jet shapes agree with perturbative QCD when the jet algorithm used in experiment and

theory is identical.

Data from e^+e^- shows that quark and gluon jets differ in shape. Data from $p\bar{p}$ tend to confirm that measurement, by showing that a larger fraction of high energy jets are quark-like, as predicted by QCD.

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